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NEW PHYSICS EFFECTS ON CP VIOLATION IN B DECAYS[★]

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We review new physics effects on CP violation in B decays. For previous reviews on this subject, we refer the reader to refs. [1, 2, 3, 4]. A discussion of CP violation in B decays within the Standard Model (and a guide to the literature) can be found in [5].

In chapter 2 we introduce our formalism, and discuss the Standard Model picture of CP violation in B decays, with special emphasis on the cleanliness of the predictions. Chapter 3 gives a general discussion of new physics effects: we point out the ingredients in the analysis that are sensitive to new physics and deduce the type of new physics that is most likely to modify the Standard Model predictions. Explicit examples are given in chapter 4: a model with Z -mediated flavor changing neutral currents (FCNC) demonstrates in which ways will new physics manifest itself in CP asymmetries in B decays; a supersymmetric model with “quark–squark alignment” mechanism shows that supersymmetry may affect CP asymmetries in B decays, even though the minimal supersymmetric Standard Model (MSSM) does not; multi-scalar models may affect the asymmetries even in the absence of new CP violating phases; schemes for quark mass matrices will be crucially tested by the CP asymmetries. In chapter 5 we explain how, if deviations from the Standard Model predictions are measured, we will be able to learn detailed features of the New Physics that is responsible for that.

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2. THEORETICAL BACKGROUND

Let us first describe our basic formalism. A more detailed discussion can be found in ref. [3]. If B and \bar{B} are the CP conjugate bottom mesons (*i.e.* B^0 and \bar{B}^0 , B^+ and B^- , B_s and \bar{B}_s), and f and \bar{f} are CP conjugate final states, then we denote by A and \bar{A} the two CP conjugate amplitudes:

$$A \equiv \langle f | H | B \rangle, \quad \bar{A} \equiv \langle \bar{f} | H | \bar{B} \rangle. \quad (1)$$

For the neutral B mesons, we define p and q to be the components of the interaction eigenstates B^0 and \bar{B}^0 within the mass eigenstates B_H and B_L (H and L stand for Heavy and Light, respectively):

$$|B_L\rangle = p |B^0\rangle + q |\bar{B}^0\rangle, \quad |B_H\rangle = p |B^0\rangle - q |\bar{B}^0\rangle. \quad (2)$$

For final CP eigenstates f_{CP} , we define the product

$$\lambda \equiv \frac{q}{p} \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}}. \quad (3)$$

The quantities $|\bar{A}/A|$, $|q/p|$ and λ are free of phase conventions and physical.

We distinguish three types of CP violation in meson decays:

(i) CP violation in decay:

$$|\bar{A}/A| \neq 1. \quad (4)$$

Here, CP violation arises from the interference between direct decay amplitudes. CP violation of the type (4) can be observed in non-leptonic charged B decays, *e.g.* a difference in the rate of $B^+ \rightarrow K^+ \pi^0$ and $B^- \rightarrow K^- \pi^0$.

(ii) CP violation in mixing:

$$|q/p| \neq 1. \quad (5)$$

Here, CP violation arises from the mass eigenstates being different from the CP eigenstates. CP violation of the type (5) can be observed in semi-leptonic neutral B decays, *e.g.* a difference in the rate of $\bar{B}_{\text{phys}}^0(t) \rightarrow \ell^+ \nu X$ and $B_{\text{phys}}^0(t) \rightarrow \ell^- \nu X$.

(iii) CP violation in the interference of mixing and decay:

$$\text{Im}\lambda \neq 0, \quad |\lambda| = 1. \quad (6)$$

Here, CP violation arises from the interference between the direct decay, $B^0 \rightarrow f_{CP}$, and the “first - mix, then - decay” process, $B^0 \rightarrow \bar{B}^0 \rightarrow f_{CP}$. Of course, $|\lambda| \neq 1$ also reflects CP violation, but it belongs to either or both of the types (4) and (5). CP violation of the type (6) can be observed in neutral B decays into final CP eigenstates that are dominated by a single weak phase, *e.g.* a difference in the rate of $\bar{B}_{\text{phys}}^0(t) \rightarrow \psi K_S$ and $B_{\text{phys}}^0(t) \rightarrow \psi K_S$.

There is a significant difference in the cleanliness of the theoretical calculations in the three types of CP violation. If a certain decay gets contributions from various amplitudes with absolute values A_i , strong phases δ_i and weak, CP violating phases ϕ_i , then

$$\left| \frac{\bar{A}}{A} \right| = \left| \frac{\sum_i A_i e^{i\delta_i} e^{-i\phi_i}}{\sum_i A_i e^{i\delta_i} e^{+i\phi_i}} \right|. \quad (7)$$

It follows that direct CP violation requires both non-trivial strong phase difference ($\delta_i - \delta_j \neq 0$) and non-trivial weak phase difference ($\phi_i - \phi_j \neq 0$). Conversely, the calculation of direct CP violation requires knowledge of strong phase shifts and absolute values of various amplitudes and, therefore, necessarily involves hadronic uncertainties.

In the neutral B system, where the width difference between the two mass eigenstates is much smaller than the mass difference,

$$\left| \frac{q}{p} \right| = 1 - \frac{1}{2} \text{Im} \frac{\Gamma_{12}}{M_{12}}. \quad (8)$$

While M_{12} is measured by the mass difference, Γ_{12} needs to be theoretically calculated. This is basically a long-distance physics calculation, and therefore involves large hadronic uncertainties. While it is clear that $|q/p| - 1$ is very small ($\mathcal{O}(10^{-3})$), the actual value is uncertain by a factor of a few [1].

In contrast, CP asymmetries of the type (6) are theoretically clean. Take, for example, the $B \rightarrow \psi K_S$ mode. The deviation of $|\lambda|$ from unity due to CP violation in mixing is, as mentioned in the previous paragraph, of order 10^{-3} . The deviation of $|\lambda|$ from unity due to direct CP violation is even smaller: not only is the penguin diagram much smaller than the tree diagram, it also carries to a good approximation the same weak phase. Thus, the interpretation of the measured CP asymmetry in terms of electroweak parameters, $a_{CP}(B \rightarrow \psi K_S) = \sin 2\beta$, is accurate to better than 10^{-3} . In other modes, where the penguin contribution differs in phase from the tree diagrams, hadronic uncertainties are larger, *e.g.* of order 10% in $B \rightarrow \pi\pi$.

The Standard Model predictions for direct CP violation in various semi-inclusive B^\pm decays are given in Table 1. We take the results for the purely hadronic modes from refs. [6, 7]. The results in these two references agree, except for the modes marked with a star, where [6] quotes very small asymmetries. The quoted values should be taken as representative numbers and not as exact predictions. The asymmetries in the radiative decays were calculated in ref. [8].

1. Direct CP Violation		
Decay	BR	a_{CP}
$\bar{b} \rightarrow \bar{u}u\bar{s}$	5×10^{-3}	0.006*
$\bar{b} \rightarrow \bar{d}d\bar{s}$	3×10^{-3}	0.005
$\bar{b} \rightarrow \bar{s}s\bar{s}$	3×10^{-3}	0.005
$\bar{b} \rightarrow \bar{u}u\bar{d}$	8×10^{-3}	-0.004*
$\bar{b} \rightarrow \bar{s}s\bar{d}$	3×10^{-4}	-0.04
$\bar{b} \rightarrow \bar{d}d\bar{d}$	3×10^{-4}	-0.04
$\bar{b} \rightarrow \bar{s}\gamma$	3×10^{-4}	0.005
$\bar{b} \rightarrow \bar{d}\gamma$	1×10^{-5}	0.1

It is difficult, however, to see how these inclusive asymmetries can be experimentally measured. It is more likely that direct CP violation would be measured in exclusive modes. On the one hand side, the asymmetries for exclusive modes could be much larger. On the other hand, their calculation suffers from larger hadronic uncertainties and is sometimes very sensitive to the value of q^2 being used. Examples of exclusive asymmetries are [6, 7]

$$\begin{aligned} a_{CP}(B^+ \rightarrow K^+ \pi^0) &\sim 0.01, \\ a_{CP}(B^+ \rightarrow K^+ K^{*0}) &\sim 0.05. \end{aligned} \tag{9}$$

Again, the Standard Model prediction is uncertain by at least a factor of a few in either direction. However, if the measured asymmetries are very large, say $\gg 0.2$, it would be very difficult to accommodate them in the Standard Model even if one stretches the hadronic uncertainties, and would probably signal new physics.

An estimate of the Standard Model value of the CP asymmetry in semi-leptonic B decays,

$$a_{SL} \equiv \frac{\Gamma(B_{phys}^0(t) \rightarrow \ell^- \nu X) - \Gamma(\bar{B}_{phys}^0(t) \rightarrow \ell^+ \nu X)}{\Gamma(B_{phys}^0(t) \rightarrow \ell^- \nu X) + \Gamma(\bar{B}_{phys}^0(t) \rightarrow \ell^+ \nu X)} = \frac{|q/p|^4 - 1}{|q/p|^4 + 1}, \tag{10}$$

can be made on the basis of quark diagrams calculation of Γ_{12} (see refs. [1, 3] and references therein):

$$\begin{aligned} a_{SL}(B^0) &\approx \frac{8\pi}{f_2(y_t)} \frac{m_c^2}{m_t^2} \frac{J}{|V_{tb}V_{td}^*|^2} \sim 10^{-3}, \\ a_{SL}(B_s) &\approx \frac{8\pi}{f_2(y_t)} \frac{m_c^2}{m_t^2} \frac{J}{|V_{tb}V_{ts}^*|^2} \sim 10^{-4}, \end{aligned} \tag{11}$$

(J is the Jarlskog measure of CP violation). The estimates (11) have hadronic uncertainties of a factor of 2–3. In addition, the estimate of $a_{SL}(B^0)$ has a large uncertainty from the poorly determined CKM parameter $|V_{td}|$. Again, a very large leptonic asymmetry, say $\gtrsim 10^{-2}$, would be difficult to explain by hadronic uncertainties and would imply new physics.

The cleanliness of CP violation in the interference of mixing and decay makes it the prime candidate for discovery of New Physics. The Standard Model predictions for various classes of asymmetries are given in Tables 2 and 3. (The signs of the asymmetries in the last column corresponds to CP even final hadronic states and not necessarily for the actual example in the first column.)

2. CP Asymmetries in B^0 Decays		
Final State	Quark Sub-Process	SM Prediction
ψK_S	$\bar{b} \rightarrow \bar{c}c\bar{s}$	$-\sin 2\beta$
D^+D^-	$\bar{b} \rightarrow \bar{c}c\bar{d}$	$-\sin 2\beta$
$\pi^+\pi^-$	$\bar{b} \rightarrow \bar{u}u\bar{d}$	$\sin 2\alpha$
ϕK_S	$\bar{b} \rightarrow \bar{s}s\bar{s}$	$-\sin 2(\beta - \beta')$
K_SK_S	$\bar{b} \rightarrow \bar{s}s\bar{d}$	0

3. CP Asymmetries in B_s Decays		
Final State	Quark Sub-Process	SM Prediction
$\psi\phi$	$\bar{b} \rightarrow \bar{c}c\bar{s}$	$-\sin 2\beta'$
ψK_S	$\bar{b} \rightarrow \bar{c}c\bar{d}$	$-\sin 2\beta'$
ρK_S	$\bar{b} \rightarrow \bar{u}u\bar{d}$	$-\sin 2(\gamma + \beta')$
$\phi\phi$	$\bar{b} \rightarrow \bar{s}s\bar{s}$	0
ϕK_S	$\bar{b} \rightarrow \bar{s}s\bar{d}$	$\sin 2(\beta - \beta')$

The various angles that appear in Tables 2 and 3 are defined by

Fig. 1. The Standard Model predictions in the $\sin 2\alpha$ (horizontal) – $\sin 2\beta$ (vertical) plane for $110 \leq m_t \leq 180 \text{ GeV}$. (The allowed ranges for all other parameters are taken from [29].)

$$\begin{aligned}\alpha &= \arg \left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*} \right], & \gamma &= \arg \left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \right], \\ \beta &= \arg \left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*} \right], & \beta' &= \arg \left[-\frac{V_{cs}V_{cb}^*}{V_{ts}V_{tb}^*} \right].\end{aligned}\tag{12}$$

Of these angles, β' is constrained to be very small,

$$|\sin 2\beta'| \leq 0.06.\tag{13}$$

The Standard Model constraints on $\sin 2\alpha$ and $\sin 2\beta$ are given in Fig. 1. (We focus on these two angles because they are likely to be measured first.)

It follows that there are several clean signals of new physics:

- (i) $a_{CP}(B \rightarrow \psi K_S)$ that is significantly smaller than +0.2 (and certainly if it is negative).
- (ii) $a_{CP}(B \rightarrow \psi K_S)$ and $a_{CP}(B \rightarrow \pi\pi)$ both significantly smaller than +0.5.
- (iii) Any of $a_{CP}(B_s \rightarrow \psi\phi)$, $a_{CP}(B_s \rightarrow \psi K_S)$ and $a_{CP}(B_s \rightarrow \phi\phi)$ above a few percent in absolute value.

3. BEYOND THE STANDARD MODEL - GENERAL

CP asymmetries in B decays are a sensitive probe of new physics in the quark sector, because they are likely to differ from the Standard Model predictions if there are sources of CP violation beyond the CKM phase of the Standard Model. This can contribute in two ways:

1. If there are significant contributions to $B - \bar{B}$ mixing (or $B_s - \bar{B}_s$ mixing) beyond the box diagram with intermediate top quarks; or
2. If the unitarity of the three-generation CKM matrix does not hold, namely if there are additional quarks.

Actually, there is a third way in which the Standard Model predictions may be modified even if there are no new sources of CP violation:

3. The constraints on the CKM parameters may change if there are significant new contributions to $B - \bar{B}$ mixing and to ϵ_K .

On the other hand, the following ingredients of the analysis of CP asymmetries in neutral B decays are likely to hold in most extensions of the Standard Model:

4. $\Gamma_{12} \ll M_{12}$. In order for this relation to be violated, one needs a new dominant contribution to tree decays of B mesons, which is extremely unlikely, or strong suppression of the mixing compared to the Standard Model box diagram, which is unlikely (though not impossible for the B_s system). The argument is particularly solid for the B_d system as it is supported by experimental evidence: $\Delta M/\Gamma \sim 0.7$, while branching ratios into states that contribute to Γ_{12} are $\leq 10^{-3}$.

5. The relevant decay processes (for tree decays) are dominated by Standard Model diagrams. Again, it is unlikely that new physics, which typically takes place at a high energy scale, would compete with weak tree decays. (On the other hand, for penguin dominated decays, there could be significant contributions from new physics.)

Within the Standard Model, both B decays and $B - \bar{B}$ mixing are determined by combinations of CKM elements. The asymmetries then measure the relative

phase between these combinations. Unitarity of the CKM matrix directly relates these phases (and consequently the measured asymmetries) to angles of the unitarity triangles. In models with new physics, unitarity of the three-generation charged-current mixing matrix may be lost and consequently the relation between the CKM phases and angles of the unitarity triangle violated. But this is not the main reason that the predictions for the asymmetries are modified. The reason is rather that if $B - \bar{B}$ mixing has significant contributions from new physics, the asymmetries measure different quantities: the relative phases between the CKM elements that determine B decays and the elements of mixing matrices in sectors of new physics (squarks, multi-scalar, etc) that contribute to $B - \bar{B}$ mixing.

Thus, when studying CP asymmetries in models of new physics, we look for violation of the unitarity constraints and, even more importantly, for contributions to $B - \bar{B}$ mixing that are different in phase and not much smaller in magnitude than the Standard Model contribution. This leads to the following general description of the potential for large effects in various directions of new physics:

1. In extensions of the quark sector, CKM-unitarity is violated and there are new contributions to $B - \bar{B}$ mixing. Potentially, large effects are possible.
2. In Supersymmetry, there are new contributions to $B - \bar{B}$ mixing. Potentially, large effects are possible. (Note, however, that in the minimal SUSY Standard Model (MSSM), FCNC and new phases are “switched-off” by hand, and no new effects are possible.)
3. In extensions of the scalar sector, there are new contributions to $B - \bar{B}$ mixing. Potentially, large effects are possible. (Note, however, that in the two Higgs doublet Model with NFC, there are no new phases, and no new effects are possible.)
4. In extensions of the gauge sector, the new gauge bosons couple universally in flavor space. Typically, the strong constraints from K -physics imply that it is unlikely to have observable effects in B -physics.

In what follows, we describe several specific examples of extensions of the Standard Model that affect CP asymmetries in B decays. The following models were discussed in detail in the literature: 4th generation quarks [9, 10, 11, 12, 13, 14]; Z -mediated FCNC [15, 16, 17], Left-Right Symmetry [18, 19]; extensions of the scalar sector [20, 21, 22, 23, 24, 25, 26]; Supersymmetry [27, 28]; schemes of quark mass matrices [29, 30]; modifications of the CKM constraints [31, 24]. Effects of new physics on direct CP violation have been studied in refs. [32, 33] and on CP violation in mixing in refs. [34, 35].

4. SPECIFIC EXAMPLES

4.1 Extra Quark Singlets [15, 16, 17]

We describe here an extension of the quark sector with an $SU(2)_L$ -singlet of charge $-1/3$. (This represents well the case when there is such an additional quark for each generation, as in E_6 models.) With this extension, all the ingredients relevant to CP asymmetries in B decays are indeed affected by new physics.

In such models, the charged current mixing matrix V is 3×4 and, most important, it is not unitary. (It is a submatrix of the unitary 4×4 matrix that relates the down mass eigenstates to the interaction eigenstates.) This leads to non-diagonal Z couplings, as the neutral current mixing matrix, $U = V^\dagger V \neq 1$. In particular,

$$U_{db} = V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} \neq 0. \quad (14)$$

Eq. (14) shows that the two ingredients relevant to CP asymmetries in B decays are indeed modified in this extension:

1. Unitarity of the CKM matrix is violated. In particular, the unitarity triangle turns into a unitarity quadrangle, with U_{db} being the fourth side.
2. There are new contributions to $B-\bar{B}$ mixing from Z mediated tree diagrams:

$$M_{12}^Z = \frac{\sqrt{2}}{12} G_F (B_B f_B^2) m_B \eta (U_{db})^2. \quad (15)$$

3. There are new sources of CP violation, as the matrices V and U depend on three CP violating phases.

It is a peculiar property of this model that all three new ingredients are related to each other. Let us define the following new two angles in the unitarity quadrangle:

$$\bar{\alpha} = \arg\left(\frac{V_{ud}V_{ub}^*}{U_{db}^*}\right), \quad \bar{\beta} = \arg\left(\frac{U_{db}^*}{V_{cd}V_{cb}^*}\right). \quad (16)$$

Then, if the Z -mediated tree diagrams dominate $B - \bar{B}$ mixing,

$$a_{CP}(B \rightarrow \psi K_S) \approx \sin 2\bar{\beta}, \quad a_{CP}(B \rightarrow \pi\pi) \approx \sin 2\bar{\alpha}. \quad (17)$$

The significant modification is then not in the new range for α and β but rather that the asymmetries now depend on new phases, $\bar{\alpha}$ and $\bar{\beta}$. As there are no experimental constraints on the values of $\bar{\alpha}$ and $\bar{\beta}$ (but only on the magnitude $|U_{db}|$), the asymmetries in (17) could have any value [15], unlike the Standard Model case described in Fig. 1. (If the extra singlet quarks are much heavier than a few TeVs, $|U_{db}|$ is expected to be very small, the Z -mediated FCNC contribute negligibly to $B - \bar{B}$ mixing, and the deviations from the Standard Model predictions are unobservably small.)

In ref. [16] it was shown that the upper bound on $|U_{sb}|$ from the UA1 measurement of $b \rightarrow s\mu^+\mu^-$ implies that the effects on CP asymmetries in B_s decays cannot be maximal. For example, the zero asymmetries predicted for various B_s decays (see Table 3), could be modified to, at most, $\mathcal{O}(0.3)$. In ref. [17] it was observed that even if the Z contributions do not dominate the mixing but are just not much smaller than the box diagrams, they could still have large effects on the asymmetries. In this case, the asymmetries in (17) would have a more complicated dependence on α , β , $\bar{\alpha}$ and $\bar{\beta}$.

4.2 Quark-Squark Alignment [36, 28]

We describe here a supersymmetric extension of the Standard Model that is different from the MSSM. In particular, the mechanism that suppresses SUSY-induced FCNC is not squark degeneracy. Instead, the quark mass matrices and the squark mass-squared matrices are naturally aligned in models of abelian horizontal symmetry [36], namely they are both approximately diagonal in the same basis. If this alignment is precise enough, the mixing matrix for quark-squark-gluino couplings is very close to the unit matrix, and FCNC are highly suppressed even if squarks are not degenerate at all.

The motivation for this extension [37] was to explain the hierarchy in the quark sector parameters,

$$\begin{aligned}
1 &\sim m_t / \langle \phi_u \rangle; \\
\lambda &\sim V_{us}; \\
\lambda^2 &\sim V_{cb}, m_d/m_s, m_s/m_b; \\
\lambda^3 &\sim V_{ub}, m_u/m_c, m_c/m_t.
\end{aligned} \tag{18}$$

(with $\lambda \sim 0.2$ these relations hold to within a factor of 2.) These relations are predicted and the alignment of quarks and squarks is precise enough to satisfy the constraints from neutral meson mixing if the mass matrices have the following form (for details see [28]):

$$M^d \sim \langle \phi_d \rangle \begin{pmatrix} \lambda^4 & 0 & \lambda^3 \\ 0 & \lambda^2 & \lambda^2 \\ 0 & 0 & 1 \end{pmatrix}, \quad M^u \sim \langle \phi_u \rangle \begin{pmatrix} \lambda^6 & \lambda^4 & \lambda^3 \\ \lambda^5 & \lambda^3 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}. \tag{19}$$

(All entries here are just order of magnitude estimates.)

Such a structure for the quark mass matrices can be a result of a horizontal (discrete subgroup of) $U(1)_a \times U(1)_b$ symmetry, that is spontaneously broken by the VEVs of two Standard Model singlet scalars:

$$S_a(-1, 0) : \frac{\langle S_a \rangle}{M} \sim \lambda; \quad S_b(0, -1) : \frac{\langle S_b \rangle}{M} \sim \lambda^2. \tag{20}$$

M is a high scale where the information about the horizontal symmetry breaking is communicated to the light quarks. An example of charge assignments that lead

to M^d as in (19) is the following:

$$\begin{aligned} & Q_1(3, 0), \quad Q_2(0, 1), \quad Q_3(0, 0); \\ & \bar{d}_1(-1, 1), \quad \bar{d}_2(2, -1), \quad \bar{d}_3(0, 0). \end{aligned} \tag{21}$$

Here, the Q_i are quark-doublet supermultiplets, while \bar{d}_i are down-quark singlet supermultiplets. The charge assignments in (21) determine the form of the squark mass-squared matrices as well. Most important for our study are the diagonal blocks in the down-squark mass-squared matrix:

$$\tilde{M}_{LL}^{d2} \sim \tilde{m}^2 \begin{pmatrix} 1 & \lambda^5 & \lambda^3 \\ \lambda^5 & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}, \quad \tilde{M}_{RR}^{d2} \sim \tilde{m}^2 \begin{pmatrix} 1 & \lambda^7 & \lambda^3 \\ \lambda^7 & 1 & \lambda^4 \\ \lambda^3 & \lambda^4 & 1 \end{pmatrix}. \tag{22}$$

The structure of M^d and \tilde{M}^{d2} allows an estimate of the mixing matrix for quark-squark-gluino interaction which, in turn, gives an estimate of the SUSY contribution to neutral meson mixing. With the mass matrices of eqs. (19) and (22), SUSY contribution to $B - \bar{B}$ mixing (with $\tilde{m} \sim m_{\tilde{g}} \sim 1 \text{ TeV}$) is about 20% of the Standard Model one. On the other hand, the SUSY contribution to mixing in the K system is negligibly small. Actually, it is small enough to obey the more stringent ϵ_K constraints even for phases of order 1.

As the SUSY diagram is, in magnitude, about 20% of $M_{12}(B^0)$ but with a phase that could be very different from the Standard Model one, the Standard Model predictions for CP asymmetries in B^0 decays may be modified by as much as 0.4, a sizable effect. On the other hand, a similar analysis for B_s mixing shows that it cannot be significantly affected by the SUSY contributions, so that the Standard Model predictions for CP asymmetries in B_s decays remain unchanged.

The quark-squark alignment mechanism has strong testable predictions, namely that squarks are not degenerate and that $D - \bar{D}$ mixing is close to the experimental upper bound. Large effects on CP asymmetries in B decays are not a necessary result of quark-squark alignment, but their measurement would be extremely useful

in distinguishing between various explicit models that incorporate this mechanism. Furthermore, the model above shows that the absence of modifications to the Standard Model predictions for CP asymmetries in B decays in the MSSM is a special property of this model and not a generic feature of SUSY models.

4.3 Charged Scalar Exchange [24]

In models of three or more scalar doublets, the mixing matrix for charged scalars contains one or more CP violating phases. This phase could, in principle, affect CP asymmetries in B decays [24]. However, recent experimental constraints imply that the effect is too small to be observed. Still, the Standard Model predictions may be violated because the constraints on the CKM parameters change.

In multi-scalar models, $B - \bar{B}$ mixing gets additional contributions from box diagrams where one or two of the Standard Model W -boson propagators are replaced by the charged scalar H propagators. This situation can be presented in the following way:

$$M_{12}(B^0) = \frac{G_F^2}{64\pi^2} (V_{td}^* V_{tb})^2 (I_{WW} + 2I_{WH} + I_{HH}), \quad (23)$$

where I_{WW} , I_{HW} and I_{HH} are functions of the intermediate particle masses (m_W , m_H and m_t) and of the Yukawa couplings. The Standard Model contribution is I_{WW} . The functions I_{HW} and, in a more significant way, I_{HH} depend on the phase in the charged scalar mixing matrix.

Let us define a phase θ_H according to

$$\theta_H = \arg(I_{WW} + 2I_{WH} + I_{HH}). \quad (24)$$

(I_{WW} is real, so that in the Standard Model $\theta_H = 0$.) The angles measured by CP asymmetries in B^0 decays will be universally shifted by θ_H . Specifically,

$$a_{CP}(B \rightarrow \psi K_S) = -\sin(-2\beta + \theta_H), \quad a_{CP}(B \rightarrow \pi\pi) = \sin(2\alpha + \theta_H). \quad (25)$$

The magnitude of this effect depends on how large θ_H is. Existing constraints

from CP violating processes, most noticeably the electric dipole moment of the neutron, still allow for very large θ_H . However, the CP violating charged scalar couplings contribute also to the CP conserving decay $b \rightarrow s\gamma$. The recent CLEO bound on the rate of this decay gives the strongest constraint on CP violation from charged scalar exchange [24]. It implies that the effect on CP asymmetries in B^0 decays cannot be larger than 2%, too small to stand out as a signal of new physics.

Modifications of the Standard Model predictions for CP asymmetries in B decays may also arise from the different constraints on CKM parameters. This holds even for two scalar doublet (type I and type II) models where indeed there are no new phases. The most significant effect is that the lower bounds on $|V_{tb}V_{td}^*|$ from $B - \bar{B}$ mixing and from ϵ_K are relaxed, because charged scalar exchange may contribute significantly. This situation is actually much more general than our specific multi-scalar framework, and the results below apply to all models with significant contributions to x_d and ϵ_K : a new region (forbidden in the Standard Model) opens up in the plane of $\sin 2\alpha - \sin 2\beta$, as shown in Fig. 2 [24]. If experiment finds a relatively low value of $\sin 2\beta$ (below 0.5) and a negative value for $\sin 2\alpha$, it may be an indication that there are significant contributions from new physics to $B - \bar{B}$ mixing, even if these contributions carry no new phases.

Multi-scalar models without NFC are much less constrained, and may give large effects on the CP asymmetries [25]. An interesting case is that of light scalars with small couplings to quarks protected by approximate symmetries, where close to zero asymmetries are expected for all B decays [26].

4.4 Schemes for Quark Mass Matrices [29]

As far as CP asymmetries in B decays are concerned, extensions of the Standard Model that provide relations between the quark sector parameters are unique: instead of relaxing the Standard Model constraints on CP asymmetries in B decays, they actually narrow down considerably the allowed ranges. This means that while none of the extensions discussed in previous sections can be excluded on the basis of measurements of CP asymmetries, schemes for quark mass matrices can.

Fig. 2. The allowed region in the $\sin 2\alpha - \sin 2\beta$ plane in the Standard Model (solid) and the new allowed region in multi-scalar models (dot-dashed).

We will not go to any details concerning the various schemes for quark mass matrices discussed here. Instead, we present in Fig. 3 [29] the predictions for $a_{CP}(B \rightarrow \psi K_S)$ and $a_{CP}(B \rightarrow \pi\pi)$ from schemes by Fritzsch (the thin black wedge in Fig. 3.a); Giudice (the black band in Fig. 3.b); Dimopoulos-Hall-Raby (the black region in Fig. 3.d); and the “symmetric - CKM” scheme (the black curves in Figs. 3.c and 3.d). (For detailed references, see [29].) It is clear from the figure that CP asymmetries in the above-mentioned modes would crucially test each of these schemes.

5. HOW TO DISTINGUISH BETWEEN VARIOUS TYPES OF NEW PHYSICS?

If deviations from the Standard Model predictions are found, how can we tell which extension of the Standard Model (among the many extensions that allow large effects) is responsible for that? In this chapter, we show that the richness of experimental measurements, reflected in the large number of modes in Tables 2 and 3, can be used to study very detailed features of the new physics that might

Fig. 3. The regions predicted by various mass matrix schemes in the $\sin 2\alpha - \sin 2\beta$ plane for $m_t =$ (a) 90 GeV, (b) 130 GeV, (c) 160 GeV, (d) 185 GeV. The Standard Model predictions are outlined in grey, and those of the various schemes in black. (See the text for details.)

affect the CP asymmetries [38, 31].

More specifically, various relations among the asymmetries do not depend on all the assumptions that go into the analysis and thus may hold beyond the Standard Model or, conversely, if they are violated can help pinpoint which ingredients must be added to the Standard Model. Here are a few examples.

(i) Violation of

$$a_{CP}(B \rightarrow D^+ D^-) = -a_{CP}(B \rightarrow \psi K_S) \quad (26)$$

(the minus sign comes from the opposite CP of the final states) would imply that (a) there is new physics contribution to $K - \bar{K}$ mixing and (b) the approximate unitarity relation $V_{ud}^* V_{us} + V_{cd}^* V_{cs} \approx 0$ (where we neglected $V_{td}^* V_{ts}$) is violated.

(ii) Violation of

$$a_{CP}(B_s \rightarrow \psi\phi) \approx 0 \quad (27)$$

would imply that there is new physics contribution to $B_s - \bar{B}_s$ mixing. As shown in ref. [38], this condition is equivalent to

$$\alpha + \beta + \gamma = \pi \quad (28)$$

(where α , β and γ are deduced from the CP asymmetries in $B \rightarrow \pi\pi$, $B \rightarrow \psi K_S$ and $B_s \rightarrow \rho K_S$, respectively).

(iii) Violation of

$$a_{CP}(B \rightarrow \psi K_S) = \sin 2\beta, \quad a_{CP}(B \rightarrow \pi\pi) = \sin 2\alpha, \quad (29)$$

(where $\sin 2\alpha$ and $\sin 2\beta$ are calculated from the constraints on the unitarity triangle) would imply that there is new physics contribution to $B^0 - \bar{B}^0$ mixing.

(iv) Violation of

$$a_{CP}(B_s \rightarrow \psi\phi) \approx a_{CP}(B_s \rightarrow \phi\phi) \quad (30)$$

would most likely imply that the approximate unitarity relation $V_{cb}^* V_{cs} + V_{tb}^* V_{ts} \approx 0$ (where we neglected $V_{ub}^* V_{us}$) is violated.

As an example, we explain the test (i) above. The phases measured by the two modes are:

$$\begin{aligned} \arg \lambda(B \rightarrow D^+ D^-) &= \arg(M_{12}(B^0)) - 2 \arg(A(\bar{b} \rightarrow \bar{c} d \bar{d})), \\ \arg \lambda(B \rightarrow \psi K_S) &= \arg(M_{12}(B^0)) - 2 \arg(A(\bar{b} \rightarrow \bar{c} c \bar{s})) - \arg(M_{12}(K^0)). \end{aligned} \quad (31)$$

It is clear that the phase of the B^0 mixing amplitude does not affect the relation of eq. (26) (even though it affects the actual values of the asymmetries). As decay

amplitudes are dominated by W -mediated tree diagrams, (26) does hold if

$$\arg(M_{12}(K^0)) = \arg((V_{cd}V_{cs}^*)^2). \quad (32)$$

This is trivially the case if $K - \bar{K}$ mixing is dominated by the Standard Model box diagram with virtual c quarks. Therefore, a necessary condition for violating (26) is a new mechanism for $K - \bar{K}$ mixing. However, the extremely small experimental value of ϵ_K implies that $\arg(M_{12}(K))/\Gamma_{12}(K) \sim 10^{-3}$. Therefore, model-independently

$$\arg(M_{12}(K^0)) \approx \arg((V_{ud}V_{us}^*)^2). \quad (33)$$

Consequently, another necessary condition for violating (26) is that $V_{ud}V_{us}^* + V_{cd}V_{cs}^* \neq 0$.

We conclude that with CP asymmetries measured in many B decay modes, we can learn many detailed features of the new physics that affects their values.

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